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Linking Inter-annual River Flow River Variability Across New Zealand to the Southern Annular Mode, 1979-2011

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Abstract

River flow constitutes an important element of the terrestrial branch of the hydrological cycle, yet knowledge regarding the extent to which its variability, at a range of time scales, is linked to a number of modes of atmospheric circulation is meagre. This is especially so in the Southern Hemisphere where strong candidates, such as El Niño Southern Oscillation (ENSO) and the Southern Annular Mode (SAM), for influencing climate and thus river flow variability can be found. This paper presents the results of an analysis of the impact of the SAM on winter and summer river flow variability across New Zealand, purposefully controlling for the influence of ENSO and the tendency for the SAM to adopt a positive phase over the last 10 – 20 years. Study results, based on identifying hydrological regions and applying circulation-to-environment and environment-to-circulation approaches commonly used in synoptic climatology, reveal a seasonal asymmetry of the response of river flow variability to the SAM; winter flows demonstrate a higher degree of statistical association with the SAM compared to summer flows. Further, because of the complex orography of New Zealand and its general disposition normal to zonal flows of moisture bearing winds, there are intra-seasonal spatial variations in river flow SAM associations with clear rain shadow effects playing out in resultant river flow volumes. The complexity of SAM river flow associations found in this study warns against using indices of large scale modes of atmospheric circulation as blunt tools for hydroclimatological prediction at scales beyond hydroclimatological regions or areas with internal hydrological consistency.

Keywords: river flow, climate, hydroclimatological variability, Southern Annual Mode, atmospheric circulation.

1. INTRODUCTION

River flow constitutes an important element of the terrestrial branch of the hydrological cycle. Understanding its inter-annual variability and associated driving mechanisms is crucial for at least two reasons. Firstly, variations in the strength of the terrestrial branch of the hydrologic cycle bears important consequences for global climate change via modification of hygrothermal properties at the catchment scale (Dettinger and Diaz 2000; Chiew and McMahon 2002; Prowse et al., 2011). Secondly, strong predictive skill derived from knowledge of climate-river flow co-variability helps inform water management practices. This is especially so in a country such as New Zealand where major sectors of the economy, such as agriculture and energy production, are water resource dependent and climatic variability presents a considerable risk management problem.

Notwithstanding the importance of understanding catchment scale processes for water resource management, large-scale modes of climatic variability are increasingly recognised as critical for determining river flow variability through their impact on regional climate variability. Amongst these modes, such as the Pacific Decadal Oscillation (PDO), the Pacific/North American Pattern (PNA), El Nino Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO), is the Southern Annular Mode (SAM) which, in the Southern Hemisphere, exerts an influence on hydroclimate at the intra-annual to inter-annual time scales (Lim and Hendon, 2015; Mariani and Fletcher, 2016; Kiem and Verdon-Kidd 2009; Raut et al., 2014; Swart et al., 2015).

The SAM (also known as the Antarctic Oscillation) is an important mode of atmospheric variability (Sallée et al., 2010; Thompson and Wallace, 2000) in the extratropical Southern Hemisphere. It involves periodic fluctuations in zonally averaged sea level pressure (SLP) between two latitudinal bands encompassing the subtropical high at around 40°S and the circumpolar trough at around 60°S. Positive polarity of the SAM is characterized by an amplified pressure gradient between the two aforementioned zonal bands, poleward migration of the mid-latitude jet stream and associated surface westerlies. It is also known to generate ocean circulation anomalies such that during a positive SAM, equatorward Ekman drift at all longitudes of the circumpolar ocean and poleward Ekman drift at around 30°S is strengthened, which in turn leads to anomalies in oceanic heat transport (Hall and Visbeck 2002). Opposite conditions prevail in the negative polarity phase of SAM. Several investigators have noted the trend towards a more positive phase of the SAM over recent decades (Marshall, 2003; Swart et al., 2015) but an unequivocal explanation for this observation remains elusive (Chang and Johnson, 2015; Ding et al., 2015; Solomon and Polvani., 2016).

An ‘annular’ or ring like feature depicts the annual mean state of the SAM. On seasonal timescales however, a zonally asymmetric structure emerges, which reaches its maximum in austral winter and spring with a minimum in summer (Fan, 2007). Fogt et al. (2012) argue this zonal asymmetry may alter regional SAM-temperature relationships. With regards to this, and despite its potential importance for determining inter-annual climate and thus hydrological variability, the nature of SAM-induced climate anomalies across New Zealand have been explored by only a few investigators. For example, Kidston et al. (2009) examined the climate anomaly response to the seasonality of SAM and found distinctly different outcomes for wind direction, rainfall and temperature between summer and winter. Renwick (2011) identified a connection between the negative SAM phase and a higher occurrence of trough-like weather conditions while more zonal and blocking weather was associated with the SAM positive phase. This work corroborates the earlier findings of Sinclair et al. (1997) who showed that the 1st EOF Southern Hemisphere pressure pattern, which resembles SAM like pressure anomalies, modulates cyclone activity in the Southern Ocean with increasing westerlies near 55°S accompanied by more cyclones in high latitudes and fewer in middle latitudes, and vice versa. At the annual time scale, Ummenhofer et al. (2007) found that during positive SAM years, New Zealand as a whole is drier than normal, with the exception of the northernmost tips of both islands. This they attribute to enhanced north-easterly flows over the country while during negative SAM years the precipitation and wind anomaly patterns are reversed. Following on from this work, Ummenhofer et al. (2009) have suggested that up to 80% of the reduction in precipitation observed across New Zealand can be accounted for by the positive trend in the SAM since the mid-1970s.

Given the extent to which SAM clearly exerts an influence on climatic variability it is surprising that the linkage between the SAM and river flow across New Zealand remains unexplored. Rather to date, modes of climatic variability of longer periodicity such as the IPO and ENSO have received more attention in terms of New Zealand hydrology (McKerchar and Pearson 1994; McKerchar et al., 1998; McKerchar and Henderson, 2003; McKerchar et al., 2010;; Mosley 2000), with the latter becoming the basis of seasonal river flow forecasts for New Zealand (Bardsley, 2016; Pearson, 2008; Singh, 2016). The main aim of this paper is therefore to investigate the extent to which seasonal austral summer (DJF) and winter (JJA) river flow at the inter-annual time scale is linked to variations in the SAM. The chief justification for this is that currently SAM possesses superior predictability to precipitation at intra-seasonal to seasonal time scales (Hendon et al., 2014; Lim and Hendon, 2015; Marshall et al., 2012; Zheng et al., 2015) as the accuracy of rainfall prediction decreases as the lead time increases beyond hydrometeorological timescales of 5-10 days (Jang and Hong, 2014; Shukla et al., 2013). This bears implications for the reliability of seasonal river flow forecasts and for assessments of the likely impacts of climate change on precipitation (Lim et al., 2016) as determined by variability and change of major modes of climatic variability. Further, as there is strong evidence that river flow characteristics are modulated by modes of atmospheric-ocean circulation variability (Marti et al., 2010; Rimbu et al., 2016; Ward et al., 2016), the efficacy of rainfall-runoff curves for river flow prediction may be somewhat compromised as they are based on a deterministic modelling of the long-term or average relationship between rainfall and runoff as opposed to a modelling of hydrological response conditioned on hydrologically relevant phases of climate variability, Indeed Beckers et al. (2016) have noted the general improvement of river flow prediction achieved when ensemble stream prediction is conditioned on ENSO state. This resonates with the general move to a seamless approach to both weather/climate and hydrological forecasting based on predictors that transcend a range of timescales (Brown et al., 2012; Tang et al., 2016; Yuan et al., 2014) with associated gains n predictability (Hoskins, 2012; Yuan et al., 2015). For these reasons and with early warning systems for extremes in mind, particularly in relation to managing hydroclimatological related risks, a number of studies have focused on detecting SAM signals in extreme event chronologies (Min et al., 2013) such as wildfire (Holz and Veblen, 2011; Mariani and Fletcher, 2016), drought (Cai et al., 2011), tropical cyclones (Diamond and Renwick, 2014) and flood producing extreme rainfall (King et al., 2014). Moreover because of its predictability and its derivation from pressure fields, which in comparison to other climate fields can be recovered more easily from historic records (Jones et al., 2009), SAM can be used effectively for climate related reconstructions such as stream flow, weather types and glacier behaviour (Allen et al., 2015; Jiang et al., 2013; Purdie et al., 2011). Overall then, seeking to increase knowledge relating to the importance of modes of atmospheric circulation variability, for hydrological processes at timescales beyond the hydrometeorological, can provide insights into the causes of seasonal to decadal hydrological variability thus facilitating not only an explanation of a region's hydrological characteristics within a broader hydroclimatological context but concomitantly open up the potential for seasonal to decadal river flow prediction. Understanding SAM river flow associations also strikes a chord with the views expressed by a range of users of climate and hydrological products relating to the need to access information on climate and water resource associations at a range of temporal and spatial scales, in order to build as a complete picture as possible of the drivers of hydrological variability (Dravitzki and McGregor, 2011; Pappenberger et al., 2013; Purdie and Bardsley, 2010).

Associated with the paper's overall aim are a number of specific objectives. These include the assembly of the requisite SAM, climate and river flow data sets, the establishment of river flow responses under contrasting SAM phases and the atmospheric circulation anomaly patterns associated with anomalously high and low river flow conditions. Accordingly this paper is organised in the following way. Section 2 describes the data sources, followed by an explanation of the so-called environment-to-circulation and circulation-to-environment approaches for investigating SAM river flow linkages. Section 3 presents a description of river flow characteristics and outlines the development of a river flow regionalization which is used as a spatial framework for the exploration of hydro-climate linkages, the focus of which will be section 4. A discussion of results will be presented in section 5 and evaluated in the context of the current understanding of hydro-climate linkages in the broader New Zealand region and beyond. Conclusions are drawn in section 6. Only austral summer (DJF) and winter (JJA) river flow are investigated in this study because these seasons demonstrate the strongest climatic responses to contrasting SAM phases. Such strong climate contrasts between SAM phases should therefore be reflected in river flow responses.

2. DATA AND METHODS

In this section the data and methodology used to explore SAM river flow associations is described. Three broad types of data are used for the 1979 – 2011 study period including indices of major modes of atmospheric circulation and time series of winter and summer river flow and temperature and precipitation across New Zealand. Time series correlation, linear regression, principal components and composite analyses were the main techniques employed. A fuller description of data and methods is presented in the following sections.

2.1 Indices of atmospheric circulation modes

The two principal modes of atmospheric circulation focused on here are the Southern Oscillation (SO) and the Southern Annular Mode (SAM). From amongst a plethora of SO and SAM indices

(Hanley et al., 2003; Ho et al., 2012) we made use of the Troup (Troup, 1965) Southern Oscillation Index (SOI) and Marshall's SAM index (Marshall, 2003). The Troup SOI (T_SOI hereafter) is the standardized mean sea level pressure (SLP) difference between Tahiti and Darwin. This was downloaded from the Australian Bureau of Meteorology (BoM) web site: ftp://ftp.bom.gov.au/anon/home/ncc/www/sco/soi/soiplaintext.html. Marshall's SAM index (M_SAMI hereafter) is a sea level pressure observation based index that uses normalized monthly zonal mean sea level pressure (SLP) differences from a total of 12 stations located at approximately 40°S and 65°S. The M_SAMI was downloaded from the British Antarctic Survey web site https://legacy.bas.ac.uk/met/gjma/sam.html.

2.2 River flow, temperature and precipitation data

In selecting river flow gauging locations four criteria were applied namely: (1) flow records are continuous over time (less than 5% of missing data), (2) river flow records must be at least 30 years in length, (3) catchment areas upstream of the river flow gauging sites have minimal human modification due to flow diversion, damming and irrigation, and (4) the flow regime has not undergone significant changes over time. The first two criteria ensures that there is a balance between spatial and temporal coverage in that the selected gauging stations adequately represent river flow patterns across the country, and possible inter-decadal variability is captured. The third criterion was applied to ensure that the river flow data represented conditions as close to "natural flow" as possible, while the last criterion acknowledges the importance of the stationarity of the river flow depth–volume rating curve such that erroneous discharge estimates do not arise due to major changes in the river channel morphology and thus cross-sectional area. Based on these criteria 40 river flow gauging locations representing 40 rivers were selected (Figure 1). For these stations daily river flow, measured in cubic metres per second, were provided by New Zealand's National Institute of Water and Atmosphere (NIWA). Daily flow data was subsequently converted into monthly and seasonal means and then logarithmically transformed to ensure normality of distribution given this is an underlying assumption in the case of the parametric statistical methods applied in this research. The river flow datasets were truncated to a common period (1979-2011) so as to maximise the number of gauging stations while meeting the minimum requirement of a 30 year record. Details regarding catchment area, winter and summer river flow coefficient of variance (CV) and location for the 40 gauging stations are listed in Table 1. Monthly mean temperature (Tmean), maximum temperature (Tmax) and total rainfall (RainT) for five stations were downloaded from the New Zealand National Climate Database available via NIWA at http://cliflo.niwa.co.nz/.

2.3 Approach and analytical methods

We tackled the analysis of SAM river flow associations following two broad strategies referred to as the environment-to-circulation (E-C) and circulation-to-environment (C-E) approaches (Yarnal, 1993). In the case of the E-C approach years with winters and summers possessing threshold based high and low river flows are first identified, followed by a consideration of the atmospheric circulation characteristics for the set of high and low river flow years. For the C-E approach, groups of years with strongly contrasting atmospheric circulation characteristics are first identified. Subsequently the magnitude of winter and summer river flows for these two contrasting groups of years is compared.

In order to reveal genuine hydro-climate linkages on the inter-annual timescale, linear trends in river flow and indices of atmospheric circulation modes were removed prior to analysis. Also in an attempt to understand the unfettered river flow response to the SAM, with respect to El Nino Southern Oscillation (ENSO) as represented by the T-SOI, multiple linear regression (MLR) of concurrent and lead SOI variables were applied to de-trended river flow time series and its proxy in the form PC scores (see below). A subsequent stepwise variable elimination (SMLR) was performed to retrieve a parsimonious model that accounts for the impact of ENSO on river flow. The final modelled river flow residuals are considered as the variability not explained by ENSO and therefore constitute the river flow time series that formed the basis of the analysis presented here; Cox (2006) has discussed extensively the use of residuals in this way to de-emphasise the importance of strong underlying drivers of environmental time series patterns.

As opposed to assessing SAM river flow associations on a SAM-individual gauging station basis, winter and summer river flow regions were identified in order to provide a spatial framework for the analysis. We used a S-mode decomposition Principal Component Analysis (PCA) based on a correlation matrix with Varimax rotation (Yarnal 1993) in the first of a two-step process to achieve a river flow regionalisation for New Zealand.

There are a number of subjective decisions to be made in applying PCA. Following Yarnal (1993) a correlation dispersion matrix was selected as the basis for identifying river flow gauging stations with covariant river flow. Of a range of rotation possibilities, including non-rotation, a Varimax rotation was performed. A Varimax rotation was selected as it is more conducive to a physical interpretation of the principal components (PC) compared to other rotations (Yarnal, 1993). Further, rotation is deemed necessary when PCA is applied in a spatial context (Richman, 1986), as it is here. An outcome of PCA is the identification of a number of principal components (1 – n, where n equals the number of original variables or gauging stations), which in decreasing order of importance explain the variability of river flow attributable to groups of gauging stations possessing similar flow variability. The relative importance of the PC in terms of the proportion of the total river flow variability explained is represented by the magnitude of a PCs' eigenvalue. In this analysis the number of PC to retain for further analysis and thus explaining the largest proportion of variability, was selected based on Kaiser's eigenvector/PC selection criterion (Jackson, 1993), that is, PCs with eigenvalues greater than unity were retained. The retained PC were used to generate a time series of PC scores which represent the covariant behaviour of river flow across the gauging stations that comprise each of the river flow regions; PC scores for each region are in effect regional river flow series. PC Scores in addition to values of the M-SAMI formed the basis of the E-C and C-E approaches applied in the split composite analysis.

In the second step the resultant loadings associated with the retained PC were subject to Cluster Analysis (CA) so as to identify groups of stations, or regions that possess river flow affinity for winter and summer. As CA can be approached in a number of ways, both partitioning and hierarchical methods were explored in the development of the final river flow regionalisation.

In doing so the following was considered: (1) K-means partitioning based on Euclidean distance, (2) Hierarchical clustering based on Euclidean distance using Average Linkage, Complete linkage or Ward's method. K-means partitioning is an iterative technique that is best used with large datasets. It is sensitive to the starting strategy and when used on a small dataset it has problems converging to a global optimum. Average linkage classifies according to the average distances between members of paired groups, and complete linkage uses a distance measure for the two farthest members in paired groups. The former does not cope well with overlap between clusters while the latter is easily affected by outliers. Ward's method is the hierarchical version of the k-means partitioning method. Although it has the tendency to form clusters of equal size, it has been shown to perform well in simulations and in practice (e.g., Stahl and Demuth, 1999; Kingston et al., 2009). By comparing the results arising from the range of clustering methods described above it was decided that the Ward's method yielded the most physically meaningful river flow regionalisation.

3. RESULTS

Three broad types of results are presented in this section. Firstly the outcome of the river flow regionalisation based on PCA and CA is described. Following this, the results from an assessment of the significance of the statistical association between times series of river flow, climate variables and the M-SAMI are presented. Lastly results arising from the application of split sample composite analyses in the broader context of the E-C and C-E approaches described above are outlined.

3.1 River flow regionalization

The PCA of summer and winter river flows for the period 1979 – 2011 produced seven PC with eigenvalues great than one, explaining 83.2% and 84% of the total river flow variance across the 40 gauging stations respectively. For summer and winter PC1, or the dominant mode of variability, accounted for 39.1 and 43.4 percent of the total variability respectively. A mapping of PC1 loadings for DJF and JJA (Figure 2) shows for summer that river flow in the Bay of Plenty, East Cape, Hawkes Bay region (Figure 2a) accounts for the greatest variability whereas in the winter (Figure 2b), the most variable region shifts westward, encompassing the broader Waikato, Taranaki and central North Island region. Although space restrictions prevent the presentation of summer and winter loading maps for the other six PCs, Table 2 summarises the percentage variance explained by each of the seven individual PC for both seasons.

The emergent river flow regionalisation based on CA of the PC loadings, comprising six winter and summer river flow regions, is presented in Figure 3. The river flow regions resemble those produced by Mosely (1981) and Beadle and McKerchar (1982), a convergence of results that lends credence to the PCA/CA based regionalisation produced here. Table 3 presents a listing of stations belonging to each river flow region. Moving from north to south the regions are named in the following way: Northland and Coromandel (NlCor), Bay of Plenty and Hawke's Bay (BoPHB), Central Western Lower North Island (CWLNI), Upper South Island (UpSI), Canterbury (CTB), and Lower South Island (LoSI). The summer/winter clusters are almost identical except for a few rivers located exclusively in the broad central North Island regions namely Tongariro, Waihohonu, Waikato and Waihou. These all become more “BoPHB like” in winter.

The general hydrological characteristics of the emergent regions are encapsulated in plots of the monthly distribution of river flow (Figure 4) for gauging stations near the statistical centroid of each of the clusters. CWLNI and NICor demonstrate a strong seasonal cycle that closely mirrors seasonal precipitation distribution in the North Island (Ummenhofer and England, 2007) with a clear summer period of distinctly lower flows compared to the winter months. The drop in flow in September suggests purely rain-fed river flow without snowmelt contribution in these two regions. Relative to its counterparts the BoPHB region in the North Island possesses a dampened seasonality of river flow, apart from the slight flow elevation July through to September often due to storms which stall off the east coast of the North Island around the East Cape region and advect moisture off the Pacific Ocean to the east. The South Island regions demonstrate clear evidence of the importance that spring snow melt water plays in the seasonal distribution of river flow. This is especially so for UpSI and LoSI where throughout the months July to October there is a steady increase in flow indicating an increasing release of water from melting high elevation snowpacks. Interestingly for UpSI and LoSI, June relative to July demonstrates on average higher flows as in June rainfall dominates the precipitation mix and is available to runoff immediately while in July much of the precipitation that falls is tied up in snow with moisture released for runoff later in the winter or in early spring. Of note for all rivers is the dominance of data points for high flow compared to low flow indicating that New Zealand rivers demonstrate most of their variability due to high as opposed to low flows. This is especially so for the winter months (Figure 4). A further explanation for the predominance of high flow data points is that while river flow is bound at the lower limit it is not so at the upper limit with the predominance of high flow data points indicating the skewed nature of monthly river flow, a feature quite typical of rivers in maritime temperate climates (Moseley and Pearson, 1997; Sturman and Tapper, 2006).

Association between SAM, climate and regional river flow

The response of regional river flow, as represented by PC scores, to the SAM and regional climate variables is assessed in this section for both summer and winter.

Table 4 presents the correlation coefficients for monthly values of SAM and climate variables correlated with river flow as represented by PC scores for DJF (Table 4a) and JJA (Table 4b) (n= 96 months). Perhaps unsurprisingly river flow is positively correlated with RainT for all regions in both summer and winter (Table 4). This contrasts with the situation regarding temperature both in terms of the sign of correlation and the universality of the river flow temperature association. For summer, although the sign of the correlation coefficients indicate a general inverse association between temperature and river flow, this association is not significant for all regions. Both BoPHB and CWLNI demonstrate no statistically significant correlations between river flow and temperature. For UpSI, CTB and LoSI however the significant inverse association between river flow and Tmean and Tmax points to the possible role of reduced effective precipitation because of high evaporation rates and thus low (high) river flows being linked with warm (cool) summers. This seems to be especially so for CTB, a particularly drought prone region, which shows a very strong inverse association between river flow and Tmax. For winter there is no consistency in the direction of association between river flow and temperature. While CWLNI river flow exhibits no apparent sensitivity to temperature, CTB and LoSI river flow demonstrate a significant inverse association with temperature, which is distinctly different to the positive relation exhibited for UpSI and BoPHB. This seemingly contradictory situation may be explained by possible differences in the way in which water is stored within a catchment and eventually delivered to the river channel. For CTB and LoSI a large proportion of winter precipitation is delivered as snow, the storage of which will be favoured in cool winters with supressed Tmax. In this case a deep snowpack and therefore high water equivalents will be available for runoff during intermittent melt periods during the winter with this reflected in elevated winter discharge levels. In the case of UpSI, which also receives considerable winter snowfall but straddles a transitional zone between rain and snow along a warming south to north temperature gradient, higher winter temperatures result in a great proportion of the precipitation being delivered as rain which is directly available for runoff. For BoPBH, in which the majority of catchments are rainfall dominated, warmer winters are associated with higher river flows via increased rainfall from warm air masses emanating from the Pacific Ocean to the east often allied with extra-tropical weather systems.

The link between the SAM and regional river flow is weak in summer. While only BoPHB shows a statistically significant association, the inverse nature of which indicates summer high flows are associated with a negative phase of SAM, the sign of the correlation suggests similar associations for UpSI and LoSI (Table 4) Compared to summer, winter river flows appear to be more responsive to variations in the SAM. The statistically significant inverse association between CWLNI and LoSI river flows and the SAM indicates that vigorous westerly flows associated with eastward moving cyclonic systems, as occur under a negative phase of the SAM, are conducive to high river flows. In the case of CTB a positive phase of the SAM increases the number of rain bearing weather systems arriving over CTB from the Pacific Ocean to the east hence explaining the positive SAM river flow associations for this region, similar to the SAM BoPHB association for summer.

Whereas correlations presented in Table 4 are for monthly values, Table 5 presents a similar analysis but at the seasonal level ($n = 32$) for DJF and JJA for concurrent and one season in advance associations between SAM and river flow as represented by PC scores. Spring (SON) SAM is found to be strongly correlated with summer (DJF) CTB river flow ($r = 0.579$) (Table 5). This may be explained with reference to regional climate as for the CTB region, a positive SAM in SON leads to lower SON temperatures ($r = -0.297$, $p = 0.05$) which in turn suppresses springtime snowmelt providing a relatively large reservoir of snow for summer melt and hence elevated flow. The negative relationship between spring SAM and summer flow found for CWLNI ($r = -0.437$), and to some extent NICor ($r = -0.210$) is most likely related to elevated soil moisture in spring due to positive rainfall anomalies associated with a negative SAM and thus elevated baseflow in summer. Although UpSI is the only region that displays statistically significant concurrent associations between the SAM and summer river flow near significant associations are evident for BoPHB and CTB, reflecting the situation found for monthly river flow (Table 4). In the case of UpSI and BoPHB (CTB) the SAM river flow association is an inverse (positive) one such that a positive (negative) SAM phase and thus below (above) average summer rainfall and possible enhanced (supressed) evaporation rates leads to reduced (increased) river flow.

At the seasonal level winter river flow is found to be influenced by the state of the SAM in the preceding and current season for both LoSI and CWLNI with both displaying a significant inverse association (Table 5). The lagged and concomitant inverse SAM river flow associations found for these two regions corroborate that found at the monthly time scale such that strong westerlies and attendant positive precipitation anomalies (SAM negative phase) are conducive to high winter flows. The positive concurrent SAM river flow association for winter BoPHB river flow is opposite to the inverse association found for summer (Table 5) suggesting a strong seasonal influence of the SAM on river flow in this region as hinted at by the monthly analyses presented in Table 4.

From the preliminary results presented here, it is tentatively proposed that CWLNI, UpSI are sensitive to changes in atmospheric circulation in both seasons while NICor, BoPHB, CTB and LoSI show a seasonally varying response.

3.2 Split sample and composite analyses

River flow SAM associations were also investigated using the so called circulation-to-environment(C-E) and environment-to-circulation (E-C) approaches (Yarnal, 1993). In the former case, river flow response is assessed relative to the state of the atmospheric circulation, while for the latter, atmospheric circulation fits criteria based on river flow. These two approaches are realized by splitting and compositing the variables (circulation state or river flow) of interest.

3.3.1 Circulation-to-environment approach

The aim of the C-E approach is to establish the nature of regional flow response associated with firstly positive and negative phases of SAM for summer and winter and secondly pronounced phases of SAM for the aforementioned seasons. The first aim was achieved by plotting the distribution of PC scores (proxies of river flow) for broad-spectrum positive and negative phases of the SAM as defined by SAM index values greater or less than zero respectively. The second aim required sub-setting seasonal SAM indices into pronounced positive and negative phases of SAM as defined by upper and lower quartile values of the seasonal SAM index, and then evaluating the resultant distribution of PC scores. A standard t-test was employed to test for the significance of any differences in river flow based on the broad-spectrum and pronounced phases of SAM. The outcomes of the C-E and E-C approaches are both presented in the form of boxplots showing the distribution of PC scores or SAM index values.

Figure 5 shows the distribution of PC scores for the broadly defined positive and negative phases of SAM. For summer (Figure 5a) the only region that demonstrates a statistically significant difference in flow between positive and negative phases of SAM is CTB such that there is a tendency for river flow to be higher (lower) under a positive (negative) phase of SAM. Although there appears to be visible SAM positive and negative phase related differences in the distribution of river flow values for BoPHB, UpSI and CWLNI, large flow variances for the two

SAM states militate against any statistically significant differences. In contrast to summer, SAM phase related differences in flow are stronger for winter (Figure 5b). T-tests reveal a strong negative association, significant at the 5 percent level, for CWLNI and LoSI and a weak positive association, significant at the 10 per cent level, for CTB and BoPHB. For pronounced phases of the SAM, the association identified for the broad-spectrum positive and negative phases are replicated with no additional regions demonstrating river flow contrasts for pronounced SAM phase differences.

3.3.2 Environment-to-Circulation Approach

The aim of the E-C approach was to establish whether distinct phases of SAM are associated with summers and winters possessing high or low river flows. A summer or winter high (low) river flow state is defined as possessing PC score values greater (less) than the 75^{th} (25^{th}) percentile value. An analysis of the difference in SAM index values between summer high and low flow years revealed no statistically significant differences although the distribution of SAM index values, as revealed by boxplots (Figure 6a), are suggestive of summer SAM river flow associations for BoPHB, CWLNI and UpSI. In contrast to summer the situation is far less equivocal for winter (Figure 6b). Statistically different distributions of SAM index values between high and low river flow states are evident for CWLNI and LoSI such that low SAM index values or a pronounced negative phase of SAM is associated with anomalously high river flows. Although not statistically significant, CTB displays a similar tendency to that of CWLNI and LoSI with the opposite evident for BoPHB.

4. DISCUSSION

A burgeoning number of studies on the association between large scale climate mechanisms and hydrological response point to the importance of a range of modes of atmospheric circulation in determining river flow variability across a number of timescales (Clarke et al, 2014; Coleman et al., 2013; Fendekova et al., 2014; Hannaford et al., 2013). Given this and the fact that precipitation and temperature variability across the southern hemisphere is responsive to SAM (Cai et al., 2011; Diamond and Renwick, 2015; Feng et al., 2015; Hendon et al., 2014; Holz et al., 2011; Lim and Hendon, 2015; Manatsa et al., 2015; Oliveira et al., 2014; Raut et al., 2014; Zheng et al., 2014), the linkages between SAM and river flow across New Zealand observed in this study appear to support the general claim that large scale climate forcings serve as remote drivers of hydrological variability. Notwithstanding this generality, the situation uncovered for New Zealand indicates clear geographical and seasonal variation in the nature of SAM river flow associations.

Of the two seasons considered, SAM river flow associations are most pronounced in winter. This seasonal asymmetry of the climatic impact of SAM has been noted by others in relation to New Zealand winter precipitation and temperature patterns (Fogt et al., 2012) but as yet has not been explored for river flow. The asymmetric seasonal response of winter flow to the SAM can possibly be understood via seasonal SAM climate associations described by Kidston et al. (2009) such that contrasting phases of the SAM have their greatest impacts on precipitation in the winter via pronounced anomalies in the westerlies and advection of moisture from the west. In addition to this, Fogt et al. (2012) hypothesise that the apparently stronger SAM climate teleconnections in winter are possibly related to the more variable background state in winter while recognising that the extent to which the seasonal zonal asymmetric structure in the SAM impacts on teleconnections is equivocal. That the seasonal asymmetry in the hydrological response to the SAM is not unique to New Zealand is supported by findings from elsewhere (Cai et al., 2011; Liess et al., 2014; Wu et al., 2015) but, as implied by the work of Fogt et al. (2012), a compelling explanation for this remains elusive.

Geographical contrasts of the impact of SAM on river flow can be explained through terrain atmospheric circulation interactions and the marked impact that orography has on wind speed and direction and thus climate anomalies across New Zealand (Kidson, 2000) and the resultant precipitation anomalies that arise from distinct phases of the SAM (Kidston et al., 2009). Focusing on winter as the season of greatest sensitivity of river flow to SAM, CWLNI and LoSI display an inverse association with the SAM while BoPHB possesses a positive association. Therefore in terms of SAM phases, when SAM is negative (positive) the CWLNI and the LoSI receive anomalously strong flows of air from the west to northwest (north to northeast) exposing these regions to moisture advection (rain shadow effect and subsidence) resulting in elevated (reduced) precipitation levels and thus high (low) river flow. Typically moisture advection from the west is associated with rapid eastwardly moving low pressure systems which track just to the south of NZ (Li et al., 2016). For the BoPHB region, lying on the eastern side of the North Island, the opposite is true such that a positive phase of the SAM results in anomalous easterly flows such that the rain shadow effect associated with a negative phase is suppressed allowing penetration of moisture off the Pacific Ocean to the east which is conducive to high river flows. This resonates with the findings of Griffiths (2011) who found that the BoPHB region generally experiences wet conditions during a positive phase of the SAM. Study findings have also revealed that the summer and winter river flow response for some regions depends on the phase of SAM in the preceding season, namely spring and autumn respectively. The one season ahead associations may well relate to antecedent hydroclimatogical factors related to the SAM phase that prime hydrological regions for either anomalously high or low river flow. This suggestion resonates with the findings of Liu et al. (2015; 2016) who have suggested that boreal autumn ocean-atmosphere conditions influenced by SAM persist into the winter with a knock-on effect regarding the nature of winter precipitation over land in the Northern Hemisphere.

The regional contrasts in the response of winter river flow described above for CWLNI, LoSI and BoPHB point to possible hydrological teleconnections between CWLNI/LoSI and BoPHB. This possibility is borne out by examination of the covariant behaviour of river flow time series for these regions as represented by PC scores (Figure 7). At times there is clear concomitant inverse behaviour in regional river flow. For example, if BoPHB is compared with the LoSI (Figure 7a) for summer, the period post 1995 is noteworthy for a number of years that show reversals in river flow response with high flow in one region matched by low flow in the other. This is also evident in winter for BoPHB and CWLNI which are geographically close and lie on opposite sides of the central axis of the North Island (Figure 7b). Such possible hydrological teleconnections or "seesaws" can be understood by examining, via an environment-to-circulation perspective, the large scale atmospheric circulation situation associated with anomalously high/low winter river flows for the CWLNI region as portrayed in Figures 8 and 9. In

Figure 8a (Figure 8b), the pressure anomaly pattern is shown for a composite of years for the upper (lower) 25 per cent of CWLNI winter river flows. Immediately apparent is the typical winter asymmetric structure of the pressure field associated with a negative SAM phase, as described by Kidston et al (2009). Notwithstanding this, of interest is the relation of the CWLNI and BoPHB regions relative to the extensive region of anomalously low pressure that stretches across NZ, associated with which is an area of anomalously strong westerly winds (Figure 9a). Such an anomalous circulation configuration will expose the west facing CWLNI region to advection of moisture from the northwest to west while the BoPHB lies in a rain shadow area to the east sheltered from rain bearing westerly flows. The pressure anomaly pattern in Figure 8b is that associated with CWLNI winter low flows. It resembles to a very high degree the pressure distribution accompanying a strong positive phase of the SAM with attendant weakened (strengthened) westerly (easterly) flows across the North Island of NZ (Figure 9b). Under such a pressure configuration and allied anomalous flow pattern, the situation as described for high flows in the CWLNI region is reversed such that the BoPHB region is exposed to moisture advection from the east, emanating from the region of anomalously high pressure over the central South Pacific, while the CWLNI lies in a rain shadow to the west. Although statistically significant concurrent correlations were not found between SAM index values and river flow for the CTB region, the sign of the monthly and one season ahead correlations are strongly suggestive of CTB high flows being consequential on a positive SAM phase (Tables 4 and 5). Given its similar geographic setting to that of BoPHB, and the SAM river flow association described above for that region as well as CWLNI and LoSI, it would appear that orographic forcing/blocking or steering play a fundamental role in controlling the hydrological outcome of strong positive and negative phases of SAM across New Zealand via its control on precipitation delivery. This claim lends credence to the hydrological implications of climatological research conducted on zonal precipitation gradients across NZ (Chater and Sturman, 1998; Kerr et al., 2015; Webster et al., 2015). Further the posited significance of distinct synoptic scale configurations of atmospheric circulation for river flow across New Zealand is supported by work conducted for similar geographical settings that evaluate the importance of orography in determining hydrological outcomes arising from contrasting phases of large scale modes of climatic variability (Luce et al., 2013; Mass et al., 2015; Siler et al., 2013; Viale and Nunez, 2011).

Lastly as implied by the above discussion, this study's findings on the impact of the SAM on river flow complement the SAM-rainfall relationships described by Kidston et al (2009) but contrast with those outlined by Ummenhofer and England (2007). Two reasons account for the discrepancy of our findings with those Ummenhofer and England (2007). Firstly we, as did Kidston et al (2009), analysed potential relationships at the seasonal timescale in contrast to Ummenhofer and England (2007) who evaluated the SAM-rainfall relationship at the annual timescale. Secondly, we consider a symmetric response of river flow to the SAM while Ummenhofer and England (2007) examined the two discrete phases independently.

5. CONCLUSIONS

This study has assessed the nature of the possible association between the SAM and river flow across New Zealand at the inter-annual timescale by implementing an approach for controlling for the likely influence of ENSO on river flow and the observed tendency for the SAM to adopt an increasingly positive phase over the length of the study period. Other notable aspects of the approach taken in exploring hydroclimatological linkages include the comparison of analysis outcomes from the so called circulation-to-environment and environment-to-circulation approaches to understanding climate-environment relationships.

Study findings confirm suspected linkages between the SAM and river flow based on known SAM influences on temperature and precipitation patterns across New Zealand and in doing so add to the growing international literature on the determinants of hydroclimatoloical variability. A component of the analysis strategy that has assisted with revealing the nature of regional scale impacts of the SAM on river flow is the development of a summer and winter river flow regionalisation. This has provided an effective spatial framework for the analyses presented here as it has facilitated the identification of groups of gauging stations that have a high degree of affinity in relation to natural flow regimes and the possibility of SAM related hydrological teleconnections across New Zealand.

Because of the complex orography of New Zealand and its general north-south orientation, in a part of the world dominated by temporally and spatially variable westerlies, it is perhaps no surprise that there is little season to season and geographical stationarity in the SAM river flow relationship. Study results have revealed winter as the season with the clearest hydrological response to SAM. These findings serve as a warning against applying knowledge based on analyses of river flow response to large scale modes of climatic variability, conducted at course geographical and temporal scales, to climate-informed long range hydrological forecasts.

Although it has been found that BoPHB and LoSI flows are correlated with SAM, as implied in the limited SAM-climate literature for New Zealand, a hypothetical assumption of an out-of-phase relationship between these two regions turns out to be too simplistic. Indeed the PC score time series suggests periodical coupling and decoupling, indicating complex driving mechanisms. Further the associations between SAM and river flow are seasonally different (notably in the BoPHB and CWLNI regions), meaning that relationships derived from one season, may not be extrapolated to other seasons. There is also clear evidence that large-scale sea level pressure and zonal wind patterns associated with SAM phases modulate regional river flow and that the SAM phase in the spring and autumn may well exert influence on summer and winter fiver flow respectively. These findings provide a persuasive argument for the inclusion of information related to the SAM in seamless river flow forecasting models for New Zealand as autumn and spring SAM conditions have the potential to provide a significant forecasting signal for NZ climate and thus river flow in the following winter and summer respectively.

This study has largely focused on the direct influence of SAM on river flow. However it is acknowledged that precipitation, temperature and land surface conditions (e.g., vegetation and soil moisture status) will moderate the influence of SAM on river flow as will topography. The effects of these moderating or “hydrological memory” factors, require investigation in future research. In a similar vein and acknowledging the likely conjoint influence of ENSO and SAM on river flow, future research on the impact of synchronous and asynchronous ENSO/SAM phases on river flow is warranted.

Although much remains to be uncovered about the hydroclimatology of New Zealand, this study has facilitated the placement of the hydrology of a number of New Zealand regions in a wider hydroclimatological context by shedding light on how the SAM, as one of a number of large scale modes of climate variability, may influence winter and summer hydrological variability at the inter-annual timescale. This type of knowledge opens up the potential for seasonal river flow prediction based on the conditioning of catchment to regional scale hydrological modelling on the large scale atmospheric circulation state.

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Table 1: River flow gauging station details. DJF is December, January, February; JJA is June. July, August. CV is coefficient of variation.

Index	Site ID	River	Catchment area (km^2)	DJF CV	JJA CV	Latitude	Longitude	Missing in %
1	46618	Mangakahia	246	0.87	0.44	-35.6297	173.851	0.81
2	46644	Wairua	544	1.24	0.60	-35.6541	174.151	2.69
3	9301	Kauaeranga	121	0.94	0.59	-37.1588	175.591	0.28
4	9213	Ohinemuri	305	0.94	0.50	-37.4165	175.715	0.24
5	43420	Waikato	12429	0.24	0.29	-37.4335	175.131	0.76
6	9205	Waihou	1130	0.27	0.29	-37.5484	175.707	0.32
7	16501	Motu	1393	0.65	0.44	-37.8655	177.632	0.27
8	15302	Tarawera	914	0.16	0.19	-37.9405	176.767	0.34
9	15514	Whakatane	1560	0.78	0.60	-38.0070	176.995	0.08
10	15412	Rangitaiki	2893	0.28	0.33	-38.0414	176.800	0.27
11	15901	Waioeka	662	0.80	0.51	-38.2257	177.314	0.71
12	15410	Whirinaki	509	0.55	0.49	-38.4802	176.748	0.56
13	33316	Ongarue	1075	0.56	0.48	-38.8638	175.238	0.00
14	1043459	Tongariro	772	0.29	0.29	-38.9963	175.814	0.00
15	21801	Mohaka	2370	0.55	0.41	-39.0751	177.129	3.86
16	1043466	Waihohonu	95.8	0.22	0.29	-39.2180	175.736	0.85
17	33107	Whangaehu	471	0.21	0.28	-39.5032	175.463	0.25
18	33111	Mangawhero	511	0.72	0.45	-39.5697	175.264	0.36
19	33301	Whanganui	6643	0.67	0.46	-39.7778	175.145	0.00
20	32702	Rangitikei	2787	0.59	0.40	-39.8108	175.808	0.00
21	29224	Waiohine	184	0.62	0.34	-41.0181	175.400	0.16
22	29202	Ruamahanga	2340	0.76	0.45	-41.1986	175.440	0.22
23	57008	Motueka	163	0.59	0.50	-41.6348	172.913	1.18
24	93203	Buller	6350	0.49	0.43	-41.8360	171.699	0.80
25	60114	Wairau	505	0.45	0.47	-41.8948	172.921	1.42
26	93207	Inangahua	234	0.56	0.48	-42.1244	171.878	0.76
27	64606	Waiau	74	0.51	0.44	-42.2214	172.650	5.74
28	62105	Clarence	440	0.63	0.40	-42.4589	172.906	0.00
29	65104	Hurunui	1060	0.51	0.42	-42.7920	172.542	0.19
30	66204	Ashley	472	1.01	0.58	-43.2316	172.217	1.34
31	66401	Waimakariri	3210	0.46	0.39	-43.4165	172.652	0.41
32	68001	Selwyn	163	0.94	0.66	-43.4652	171.894	4.19
33	69618	Opihi	406	0.81	0.72	-44.1698	170.942	2.25
34	69621	Rocky Gully	22.4	0.83	0.79	-44.3260	170.774	4.86
35	71103	Hakataramea	899	1.01	0.96	-44.7262	170.490	0.46
36	75262	Kawarau	4302	0.34	0.33	-45.0081	168.868	0.70
37	78607	Oreti	1139	0.57	0.45	-45.7178	168.428	0.10
38	75232	Pomahaka	1924	0.81	0.45	-46.0607	169.401	0.00
39	77504	Mataura	766	0.62	0.42	-46.1000	168.949	0.05
40	75207	Clutha	20582	0.35	0.23	-46.2385	169.748	0.11

Table 2: Principal Components Analysis results showing percentage variance explained by seven principal components. DJF is December, January, February; JJA is June. July, August.

Principal Component	DJF	JJA
PC1	39.1	43.4
PC2	17.2	14.2
PC3	10.1	8.3
PC4	5.8	6.6
PC5	4.8	5.5
PC6	3.7	3.4
PC7	2.9	2.7
Total	83.5	84.1

Table 3: River flow regions and associated gauging station membership. CWLNI is central west lower North Isalnd, CTB is Canterbury, NICor is Northland Coromandel, LoSI is lower South Island, UpSI is upper South Island, BoPHB is Bay of Plenty Hawkes Bay.

CWLNI	CTB	NICor	LoSI	UpSI	BoPHB
Ongarue	Ashley	Mangakahia	Kawarau	Motueka	Motu
Whangaehu	Selwyn	Wairua	Oreti	Wairau	Waioeka
Mangawhero	Opihi	Kauaeranga	Mataura	Waiau	Whakatane
Whanganui	Rocky Gully	Ohinemuri	Pomahaka	Clarence	Rangitaiki
Rangitikei	Hakataramea	Waihou (6)	Clutha	Hurunui	Tarawera
Waiohine				Waimakariri	Whirinaki
Ruamahanga				Buller	Mohaka
Tongariro (6)				Inangahua	
Waihohonu (6)					
Waikato (6)					

Table 4: Climate and river flow correlations for (a) DJF and (b) JJA.. SAM is Southern Annular Mode, RainT is total rainfall, Tman is mean temperature, Tmax is maximum temperature. DJF is December, January, February; JJA is June. July, August. * and ** indicate statistical significance at the 0.05 and 0.01 levels respectively.

(a) DJF	SAM	RainT	Tmean	Tmax
NICor	-0.039	-	-	-
BoPHB	-0.190*	0.471**	-0.04	-0.165
CWLNI	0.127	0.197**	-0.099	-0.164
UpSI	-0.142	0.294**	-0.305**	-0.393**
CTB	0.11	0.559**	-0.446**	-0.618**
$LoSI_{PC4}$	-0.137	-0.114	-0.180*	-0.148
$LoSI_{PC6}$	-0.079	0.437**	-0.237**	-0.291**

(b) JJA	SAM	RainT	Tmean	Tmax
NICor	0.019	-	-	-
BoPHB	0.101	0.561**	0.207**	0.098
$CWLNI_{PC1}$	-0.226**	0.197**	-0.006	-0.109
$CWLNI_{PC6}$	-0.256**	0.424**	0.15	0.042
UpSI	0.005	0.572**	0.496**	0.441**
CTB	0.192*	0.549**	-0.12	-0.290**
LoSI	-0.177*	0.485**	-0.063	-0.234**

Table 5: Concurrent and one season ahead SAM river flow associations at the seasonal level for DJF and JJA (n = 32). * and ** indicate statistical significance at the 0.05 and 0.01 levels respectively. SON is September, October, November while MAM is March, April, May.

	DJF River flow		JJA River flow	
Region	**SON SAM**	**DJF SAM**	**MAM SAM**	**JJA SAM**
NICor	-0.210	-0.09	-0.053	0.117
BoPHB	0.180	-0.283	-0.055	0.354**
CWLNI	-0.437**	0.181	-0.207	-0.360**
UpSI	0.119	-303*	0.001	0.036
CTB	0.537**	0.267	-0.080	0.048
LoSI	0.176	-0.090	-0,455**	-0.312*

Figure 1: River flow gauging stations selected for the analysis

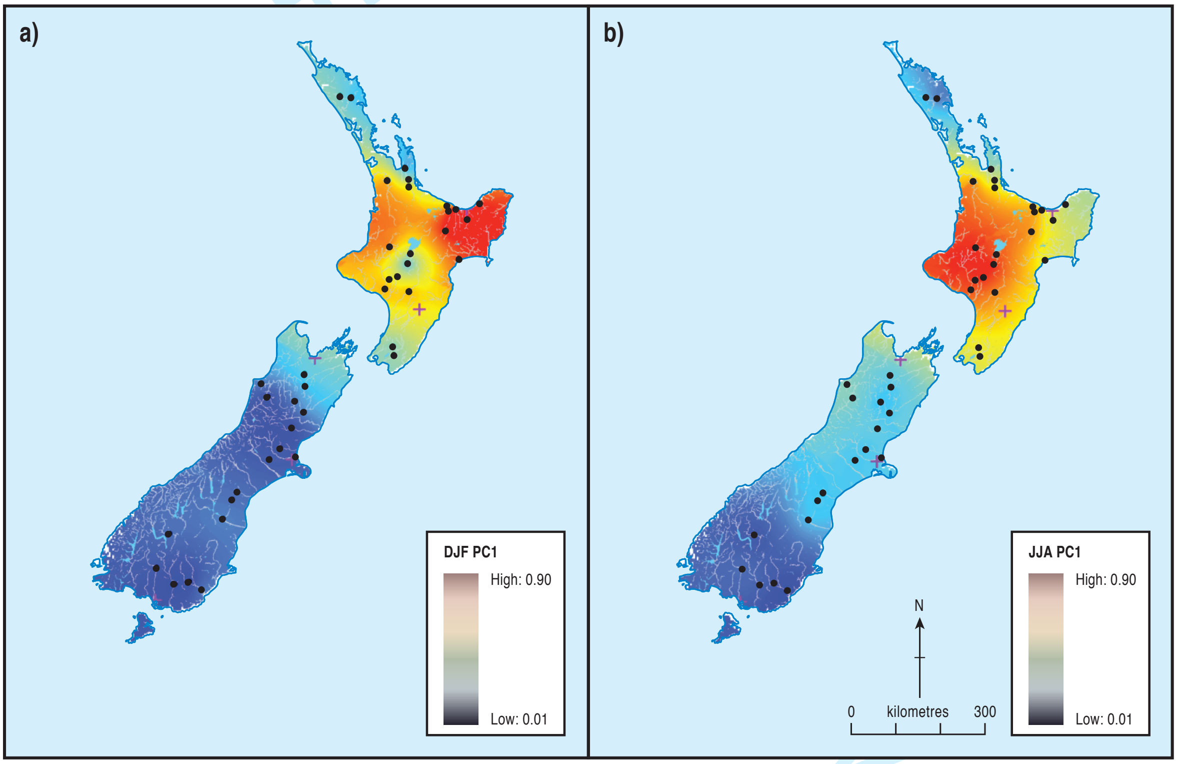

Figure 2: Principal component one loading maps for (a) DJF and (b) JJA.

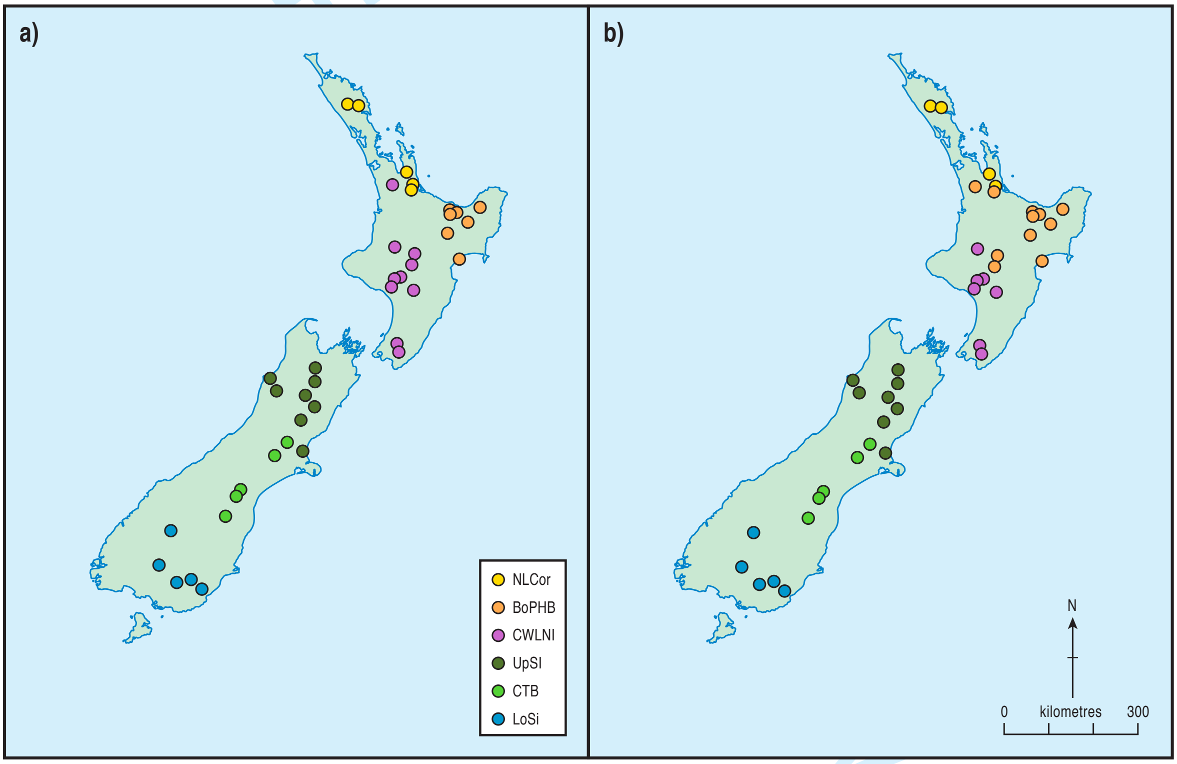

Figure 3: River flow regionalisation for (a) DJF and (b) JJA. See Table 3 for river flow region membership

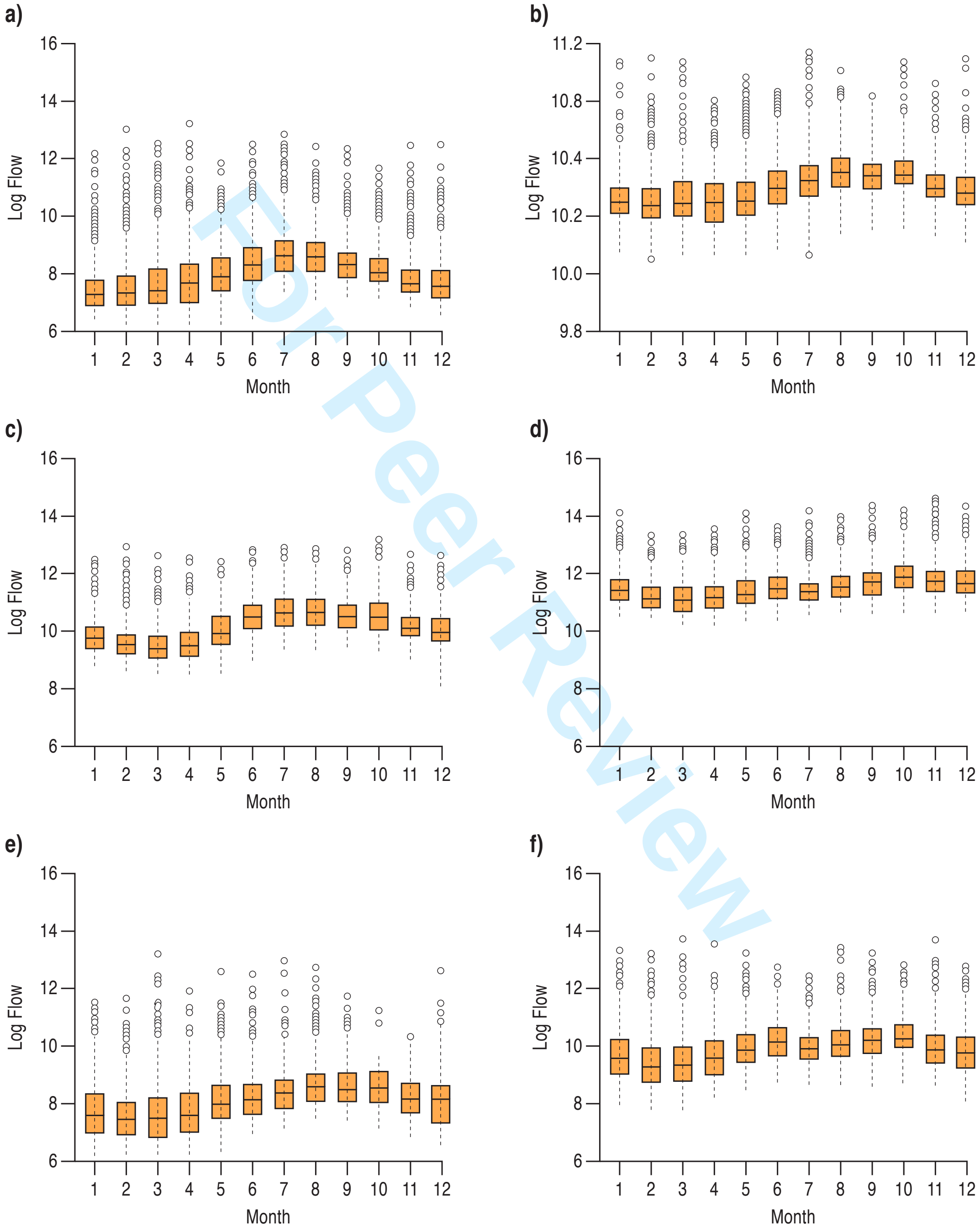

Figure 4: Seasonal distribution of river flow as portrayed by representative gauging stations for the six river flow regions. Vertical axis is the logarithm of flow. (a) Kauarenga River, NICOR region; (b) Tarawera River, BOPHB region; (c) Ongarue River, CWLNI region; (d) Waimakariri River, UPSI region; (e) Hakataramea River, CTB region; (f) Oreti River, LOSI region. In the box plots the central bar is the median value while the upper and lower bars of the box plot are the 75th and 25th percentile respectively. The lines below and above the box represent the lowest datum still within the1.5 inter-quartile range (IQR) of the lower quartile, and the highest datum still within the1.5 IQR of the upper quartile. The open circles represent data points beyond the 1.5 quartile range.

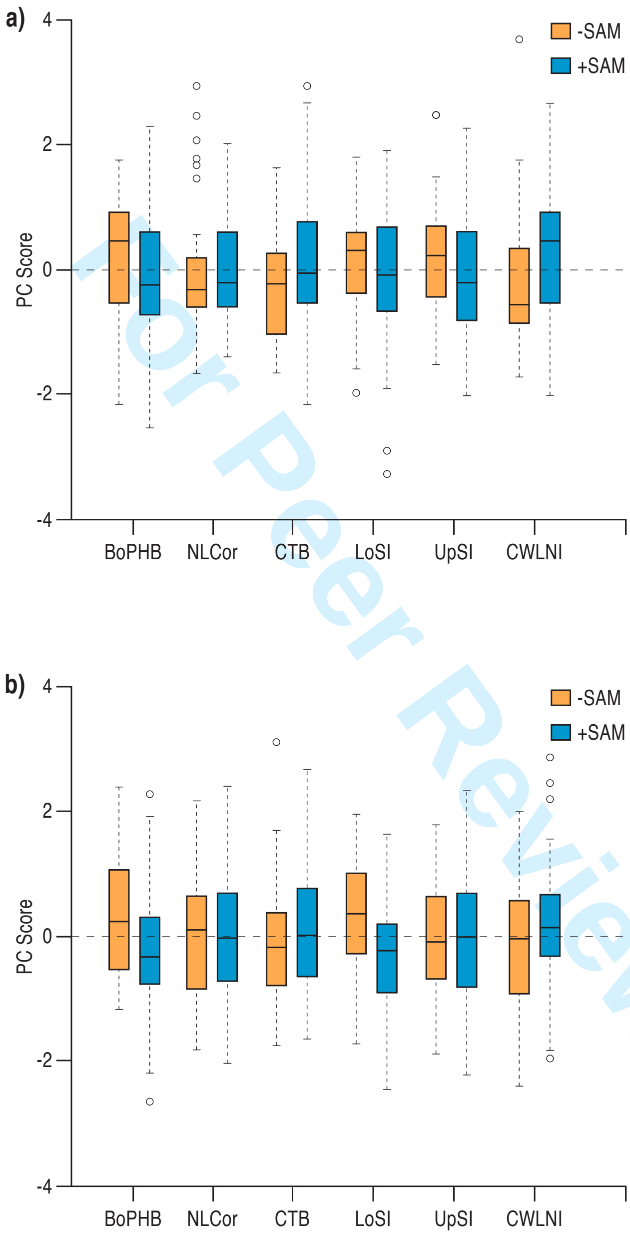

Figure 5: Principal component score (as a proxy of river flow) distribution by region for positive (+SAM) and negative (-SAM) phases of SAM for (a) DJF and (b) JJA as revealed by the circulation to environment approach.The form of the box plots is as described for Figure 4.

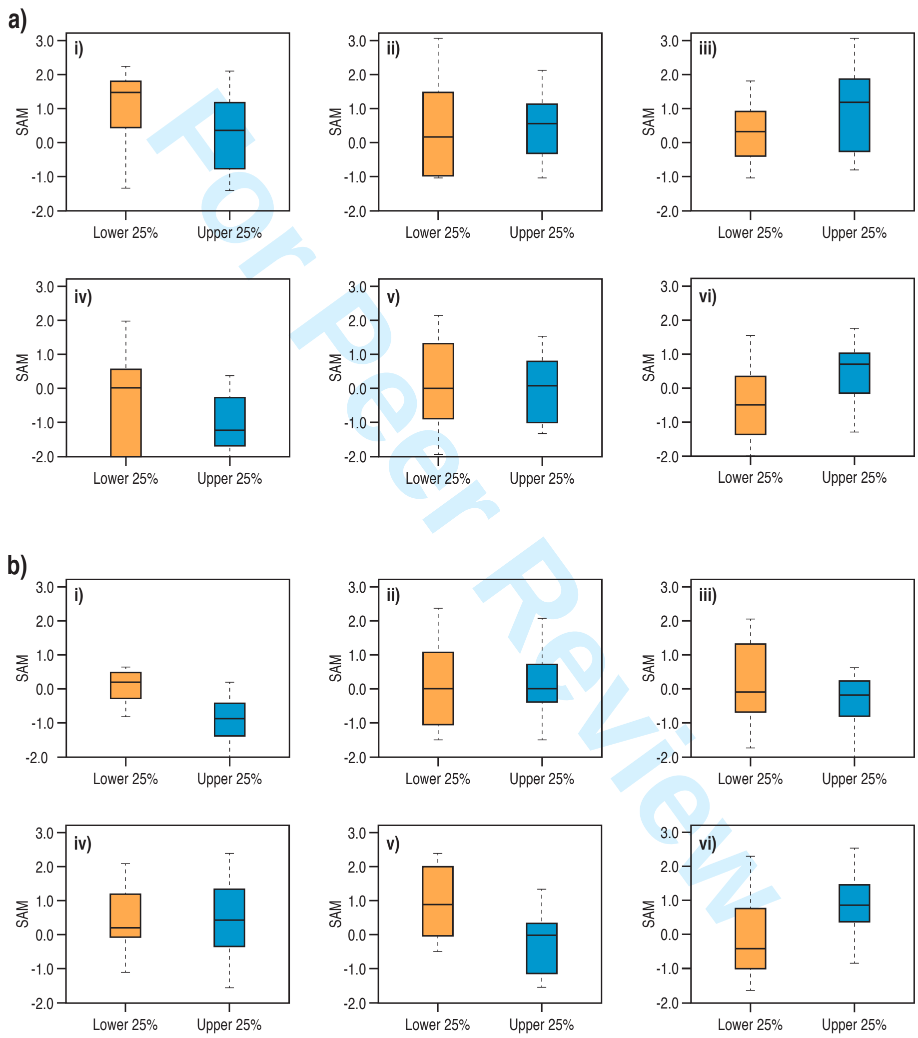

Figure 6: Distribution of SAM Index values for high and low PC scores (proxy for river flow) for (a) DJF and (b) JJA for six river flow regions as revealed by the environment to circulation approach. For DJF (a) (i) is BOPHB region; (ii) is NICOR region; (iii) is CTB region; (iv) is UPSI region; (v) is LOSI region; (vi) is CWLNI region. For JJA (b) (i) is CWLNI region; (ii) is UPSI region; (iii) is CTB region; (iv) is NICOR region; (v) is LOSI region; (vi) is BOPHB region. The form of the box plots is as described for Figure 4.

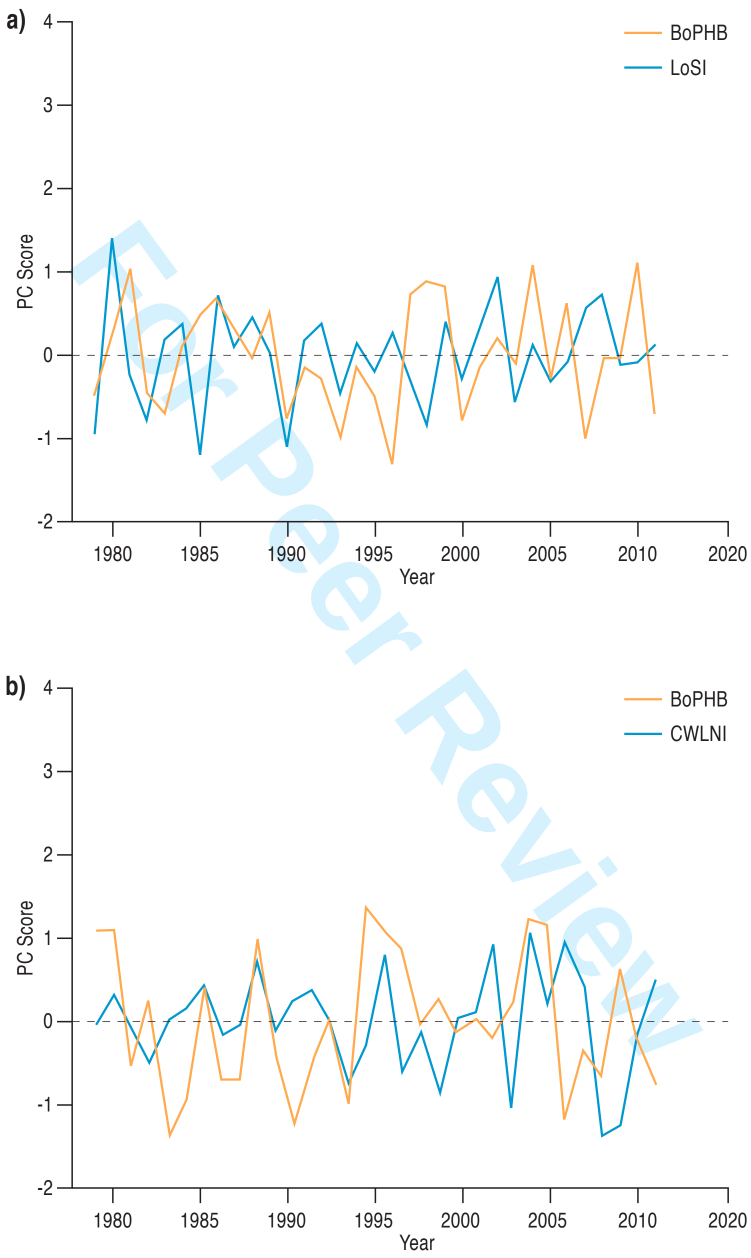

Figure 7: Time series plots of PC scores (proxy of river flow) for (a) Summer: BoPHB and LoSI regions and (b) Winter: BoPHB and CWLNI regions.

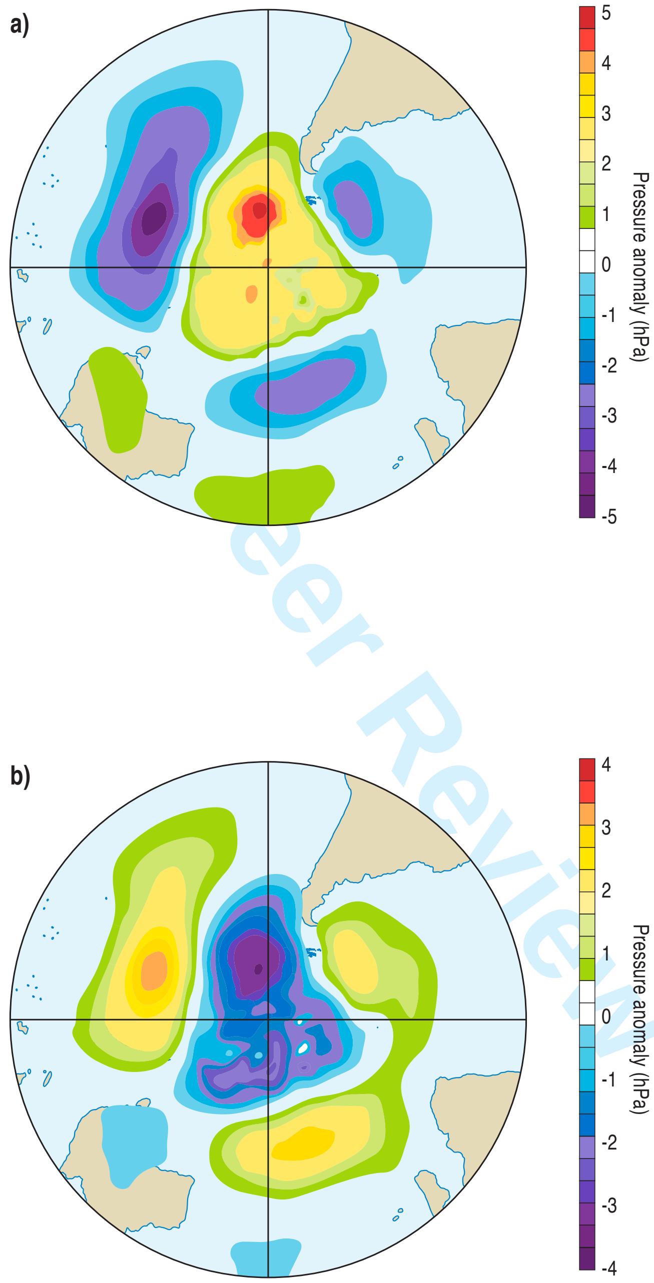

Figure 8: Sea level pressure anomaly plots for (a) upper and (b) lower 25 percent of CWLNI river flows. Plots are based on 20th Century Reanalysis V2 data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/

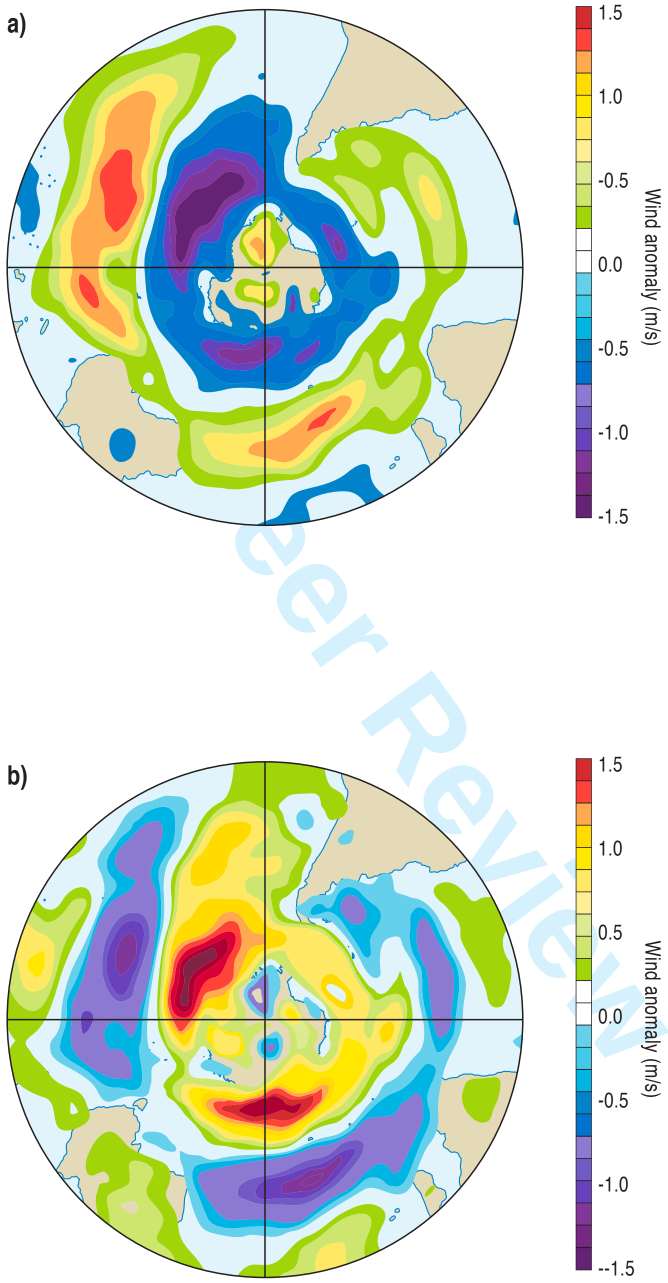

Figure 9: Wind anomaly plots for (a) upper and (b) lower 25 percent of CWLNI river flows. Plots are based on 20th Century Reanalysis V2 data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/